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Manipulations for delivering HIF beams onto targets:
(1) Smoothing by arc wobblers
(2) Differential acceleration in final beam lines*

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Abstract

We describe two techniques related to the delivery of the ion beams onto the target in a Heavy Ion Fusion power plant.

(1) By manipulating a set of ion beams upstream of a target, it is possible to achieve a more uniform energy deposition pattern. We consider an approach to deposition smoothing that is based on rapidly "wobbling" each of the beams back and forth along a short arc-shaped path, via oscillating fields applied upstream of the final pulse compression [A. Friedman, *Phys. Plasmas* **19**, 063111 (2012)]. Uniformity is achieved in the time-averaged sense; the oscillation period must be sufficiently shorter than the target's hydrodynamic response timescale . This work builds on two earlier concepts: elliptical beams [D. A. Callahan and M. Tabak, *Phys. Plasmas* **7**, 2083 (2000)]; and beams wobbled through full-circle rotations [*e.g.,* R. C. Arnold, *et al.*, *Nucl. Instr. and Meth.* **A 199**, 557 (1982)]. Arc-based smoothing remains usable when the geometry precludes full-circle wobbling, *e.g.*, for the X-target [E. Henestroza, B. G. Logan, and L. J. Perkins, *Phys. Plasmas* **18**, 032702 (2011)] and some distributed-radiator targets.

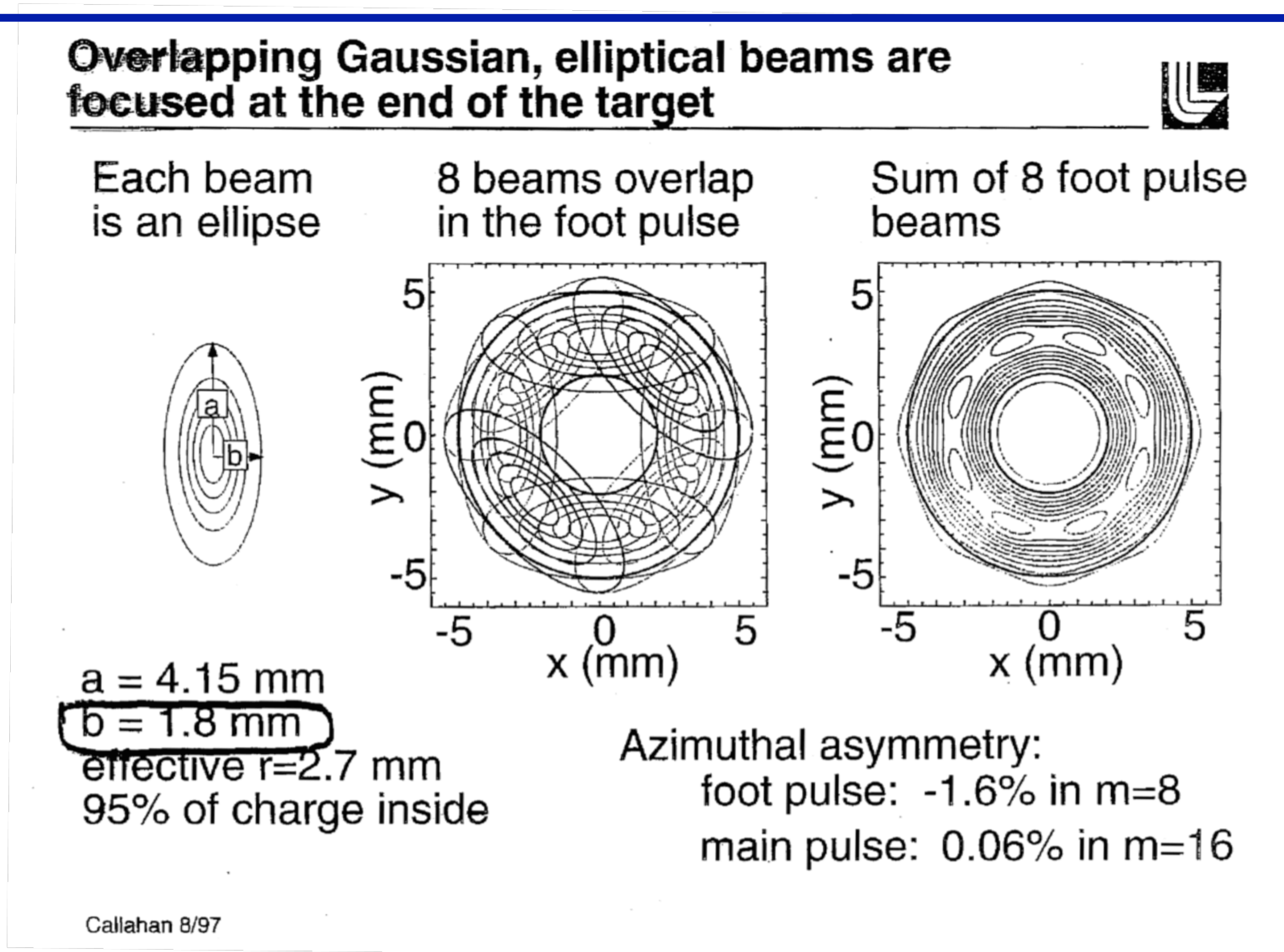
(2) By accelerating some beams "sooner" and others "later," it is possible to simplify the beam line configuration in a number of cases. For example, the time delay between the "foot" and "main" pulses can be generated without resorting to large arcs in the main-pulse beam lines. This may minimize beam bending, known to be a source of emittance growth in space-charge-dominated beams. It is also possible to arrange for the simultaneous arrival on target of a set of beams (e.g., for the foot-pulse) without requiring that their path lengths be equal. This may ease a long-standing challenge in designing a power plant, in which the tens or hundreds of beams entering the chamber all need to be routed from one or two multi-beam accelerators or transport lines.

“Arc wobbler” approach to a smoother energy deposition pattern

- This work builds on two earlier concepts:
  - Elliptical beams
    D. A. Callahan and M. Tabak, *Phys. Plasmas* **7**, 2083 (2000).
  - Beams that are “wobbled” by upstream oscillating deflecting fields so as to trace a number of full turns around a circular or elliptical path
    Arnold, Sharkov, Piriz, Basko, Tahir, Kawata, Runge, Logan, Qin, Seidl, Hoffmann, Bret ...
  - We sought a wobbled-beam concept that is applicable when the geometry precludes passing the beams around a circle, *e.g.*, as in the X-target.
  - In our “arc wobbler” approach,* beam centroids are deflected back and forth along short arcs centered upon their nominal aiming points.
- We compare this to the elliptical beam approach, for minimization of azimuthal symmetry, assuming a ring of beams arranged on a cone.

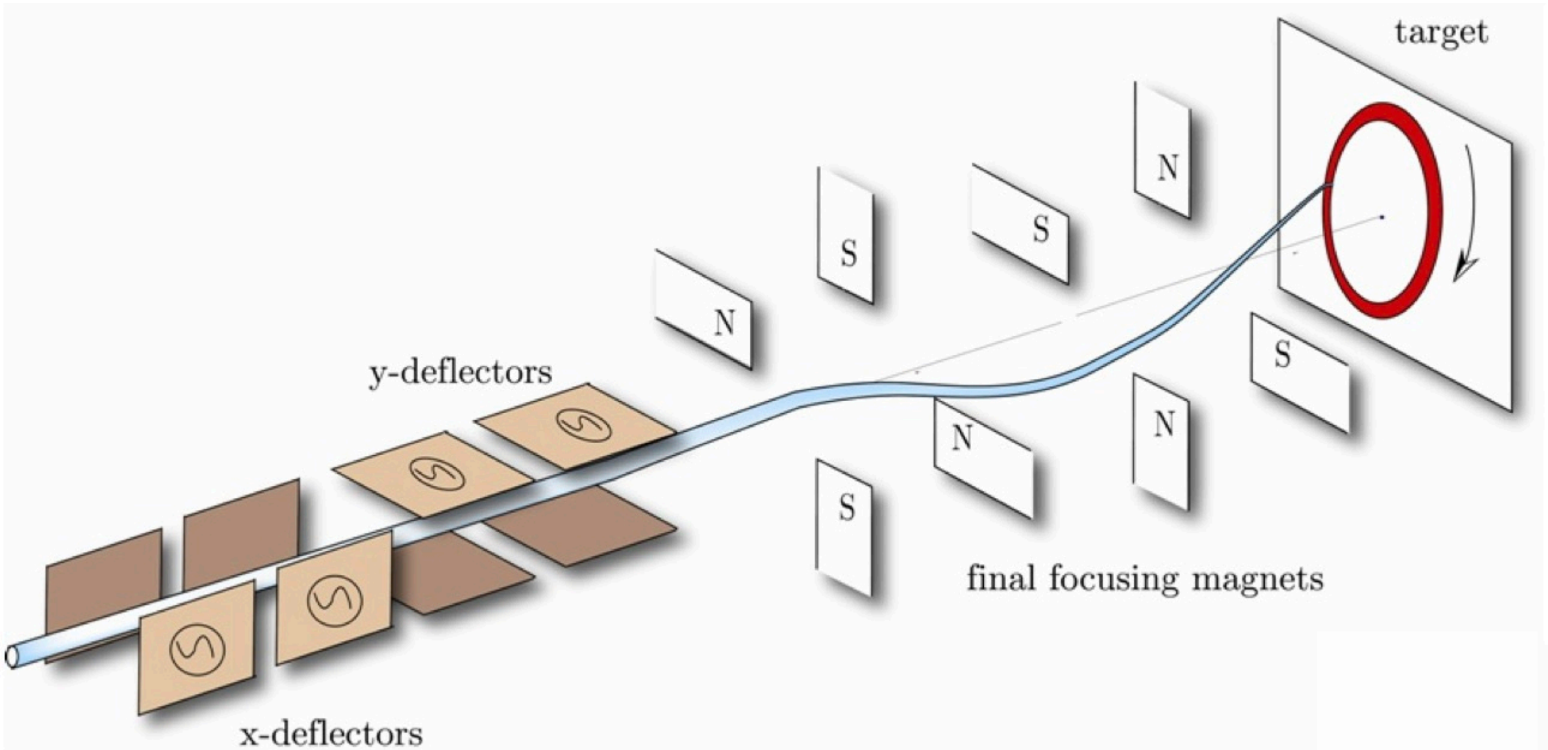
*Alex Friedman, “Arc-based smoothing of ion beam intensity on targets,” *Phys. Plasmas* **19**, 063111 (2012).

Elliptical beams were directed at the ends of Callahan and Tabak's 1997 "distributed radiator" target

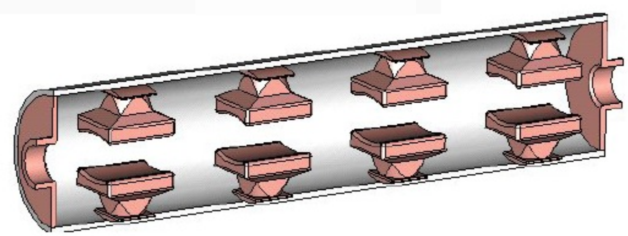


- Each beam is defocused along one axis (stretched along the tangent to the annulus).
- This was conjectured to ease requirements on beam quality, provided emittance could be "traded" between the transverse directions while conserving the 6-D phase space volume.
- This is no longer thought to be the case.
- Still, such processes as beam neutralization are likely to be eased by the reduced beam density.

RF wobbler concept

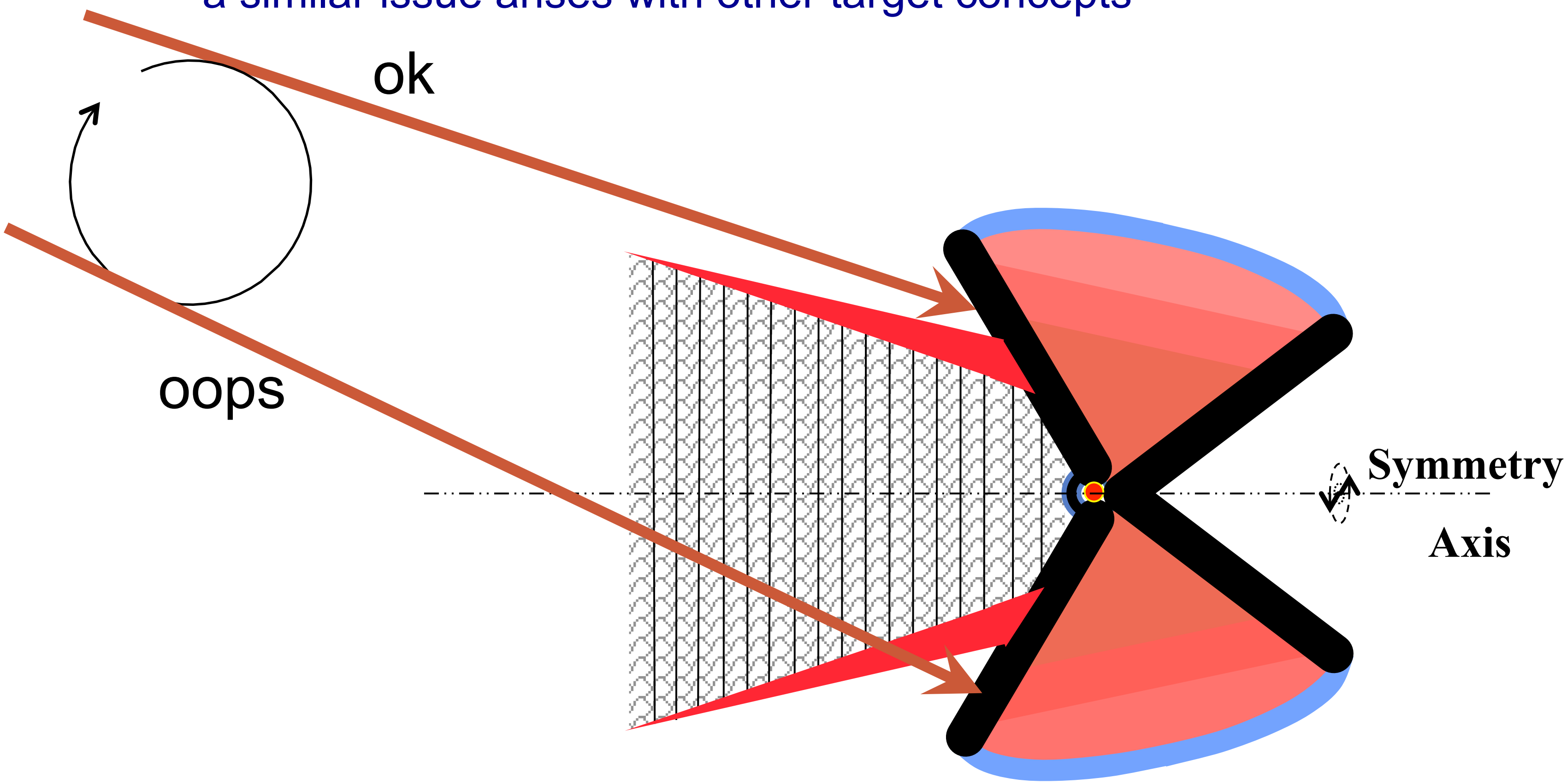


4-cell deflecting RF cavity design
(deflection along a single axis)
From: FAIR Technical Proposal GSI

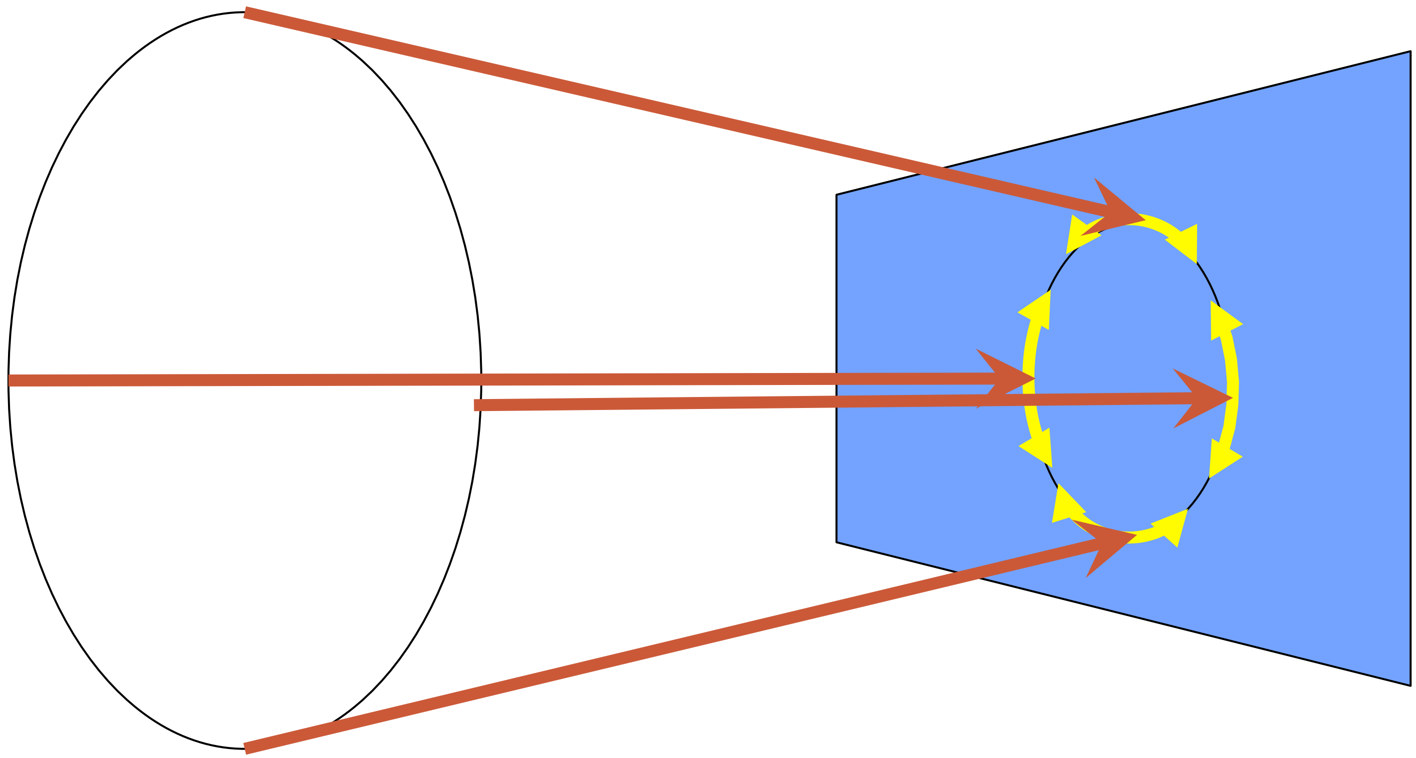


The final lens that is attached to the X-target for the igniter beams precludes full-circle beam wobbling

Also, the angle of incidence into the target is “wrong” – and a similar issue arises with other target concepts

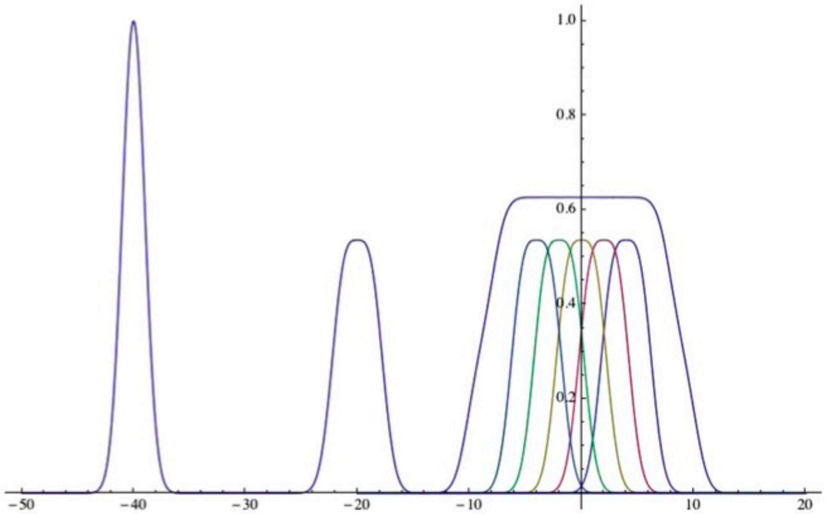


Proposed "local wobbler" geometry



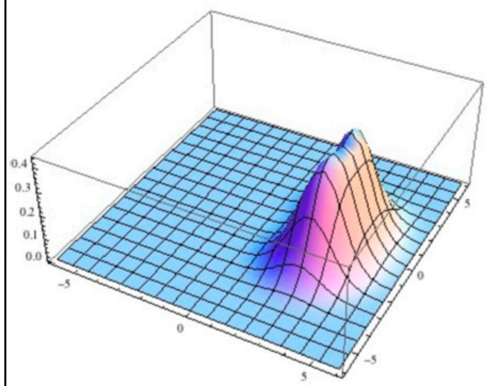
- Wobbling along circular arcs – "arc wobbling" – is depicted above.
- We have also considered a practical approach to this using RF deflector fields at a base frequency in x and twice that in y – "two harmonic wobbling."
- Simple linear wobblers were also examined.

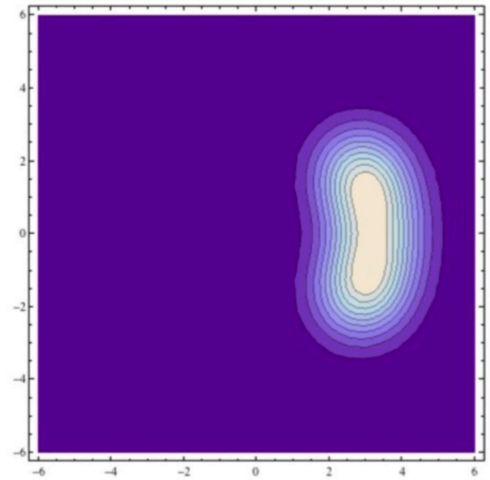
Arc-wobbled beam concept



One-dimensional example of locally wobbling beams. From left to right:

- unperturbed Gaussian
- wobbled Gaussian
- five overlapping wobbled Gaussians
- (on top) one half the sum of the five

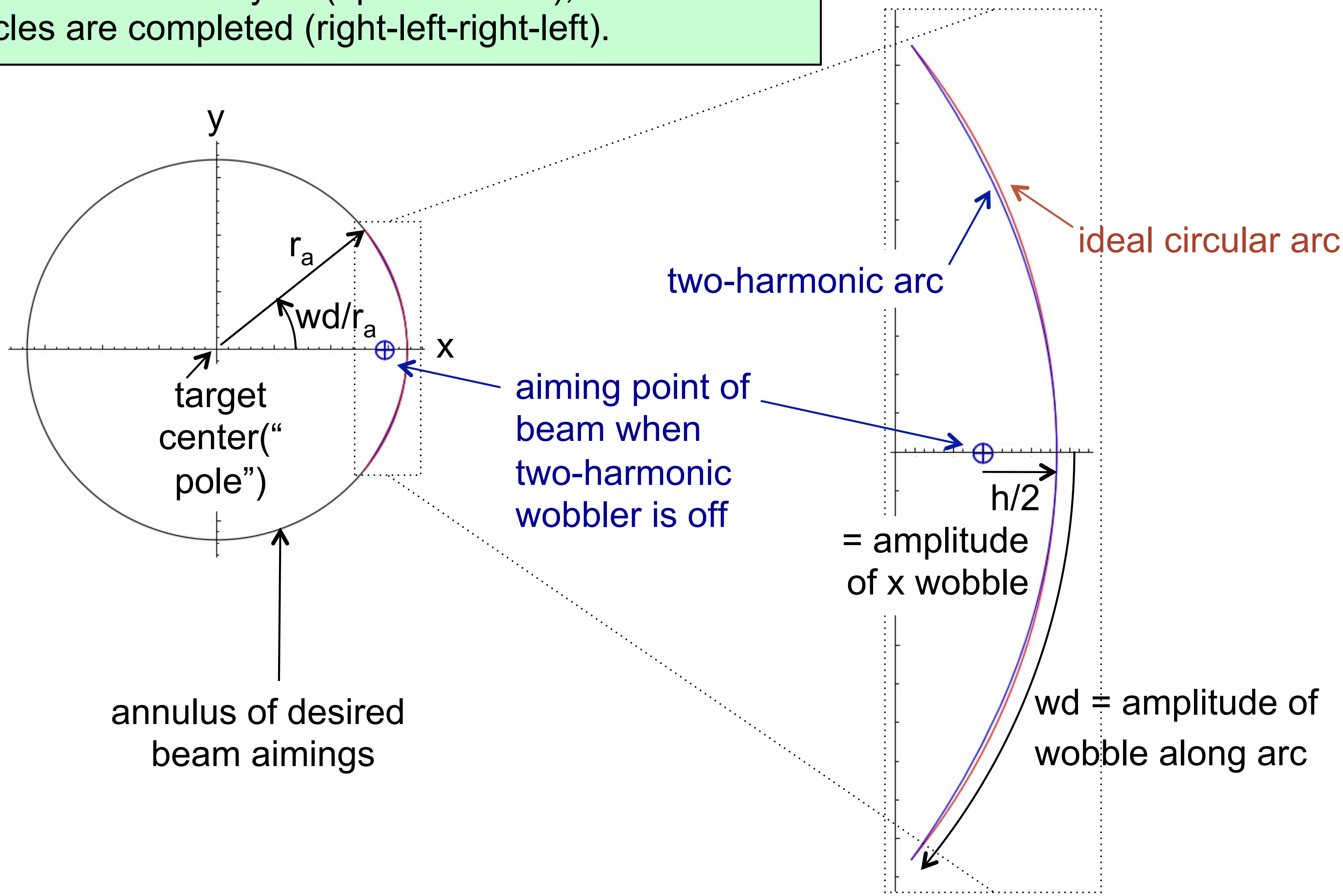




Time-averaged intensity of a single two-harmonic arc-wobbled beam, one of a set of four

For a two-harmonic wobbled beam, the tangential coordinate y oscillates at ω, while the quasi-radial coordinate x oscillates at 2ω

For each vertical cycle (up then down), two horizontal cycles are completed (right-left-right-left).



Two-harmonic wobbled beam: the equations

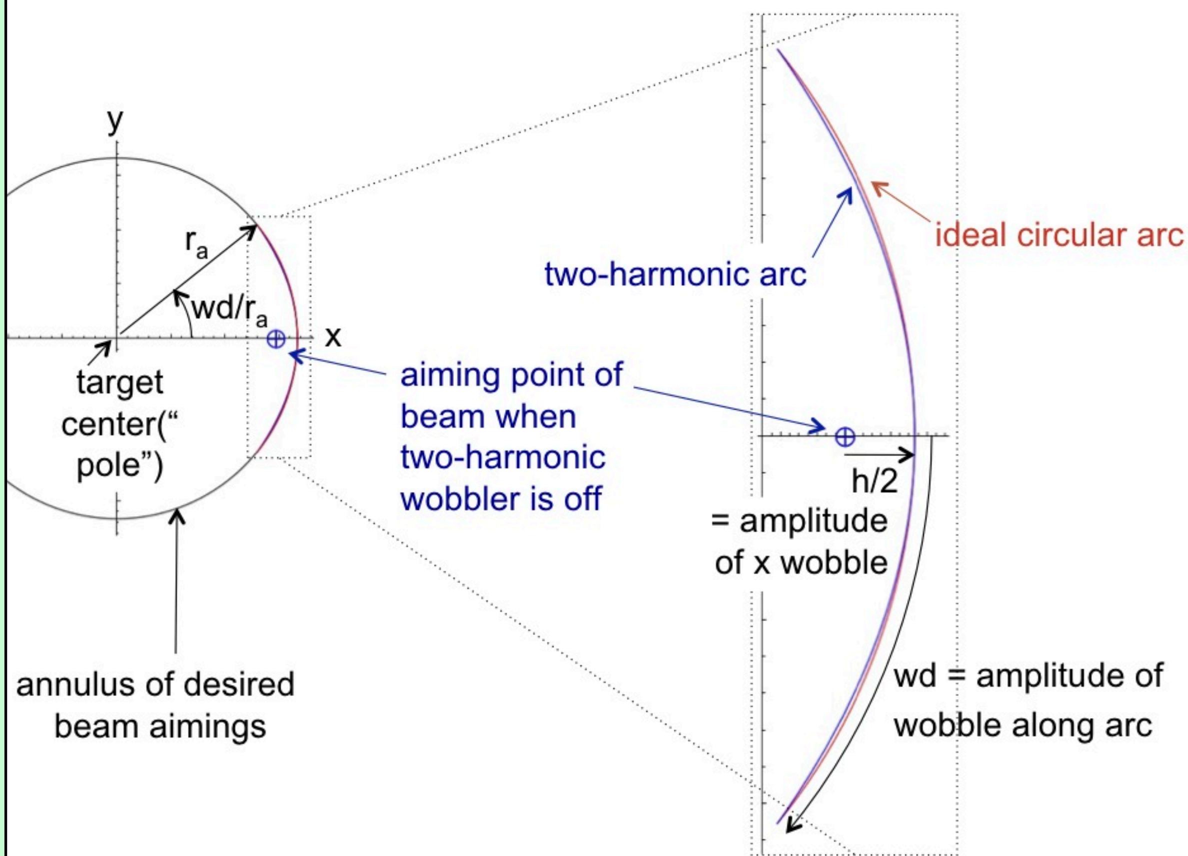
Circular arcs:

$$\text{For } -\frac{wd}{r_a} \le \eta \le \frac{wd}{r_a},$$
$$x = r_a \cos(\eta),$$
$$y = r_a \sin(\eta),$$

Two-harmonic arcs:

$$\text{For } 0 \le t \le 1,$$
$$x_{\text{aim}}(t) = r_a - \frac{h}{2}[1 + \cos(2\pi t)],$$
$$y_{\text{aim}}(t) = -r_a \sin\left(\frac{wd}{r_a}\right)\cos(\pi t),$$

$$h = r_a\left[1 - \cos\left(\frac{wd}{r_a}\right)\right].$$



Measures of nonuniformity

- Fourier decomposition around the azimuth of the radially integrated intensity; the m^{th} cosine component is:

$$C_m = \frac{\int_0^\infty \int_0^{2\pi} r \cos(m\theta) f[x(r,\theta), y(r,\theta)] d\theta dr}{\int_0^\infty \int_0^{2\pi} r f[x(r,\theta), y(r,\theta)] d\theta dr}$$

- Peak-to-valley variation on the "rim" radius (containing the peak intensity):

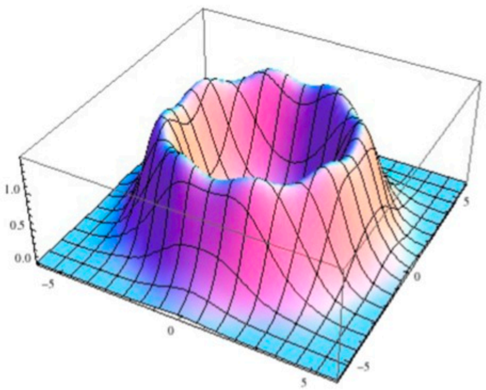
$$PTV_{\text{rim}} = 2\frac{\max_\theta f(r_{\text{rim}}, \theta) - \min_\theta f(r_{\text{rim}}, \theta)}{\max_\theta f(r_{\text{rim}}, \theta) + \min_\theta f(r_{\text{rim}}, \theta)}$$

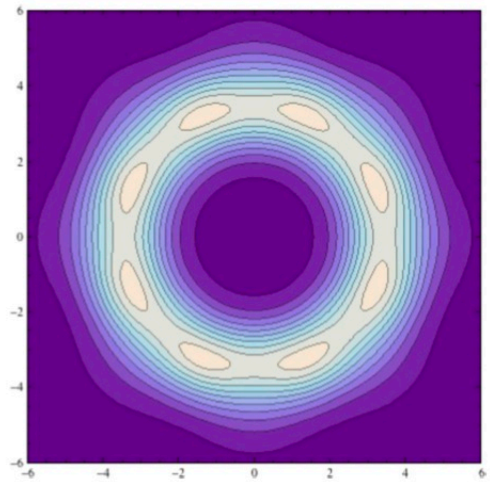
- Peak-to-valley variation of the radially integrated intensity:

$$f(\theta) = \int_0^\infty r f(r,\theta) dr,$$

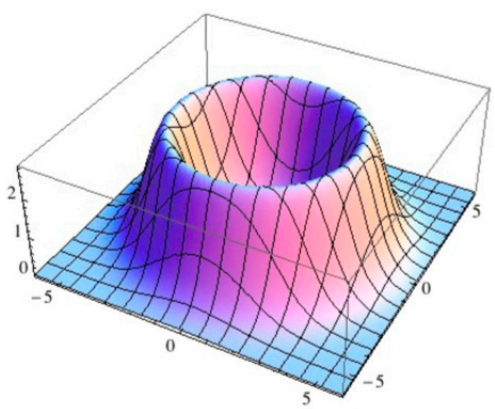
$$PTV_{\text{integrated}} = 2\frac{\max_\theta f(\theta) - \min_\theta f(\theta)}{\max_\theta f(\theta) + \min_\theta f(\theta)}$$

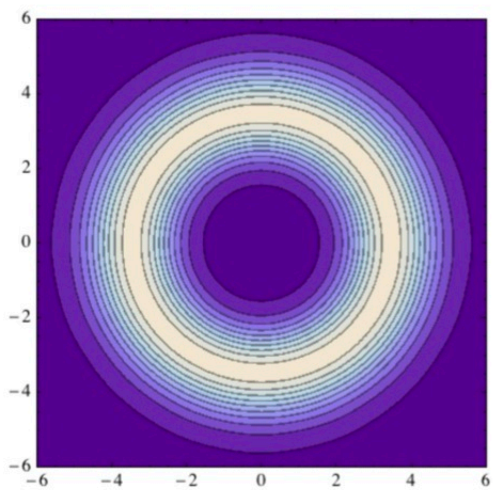
Elliptical beam examples





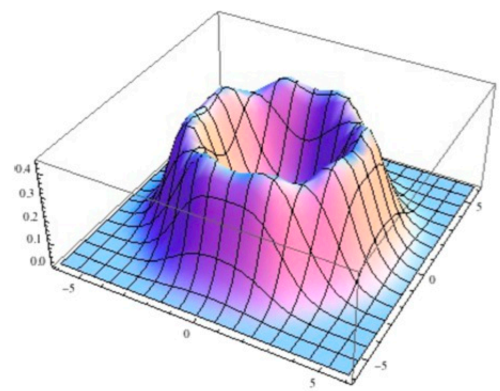
- 8 elliptical beams,
  a = 4.15 mm, b = 1.8 mm
  C_8 = -0.0051
  PTV_{rim} = 0.097
  $PTV_{integrated}$ = 0.020

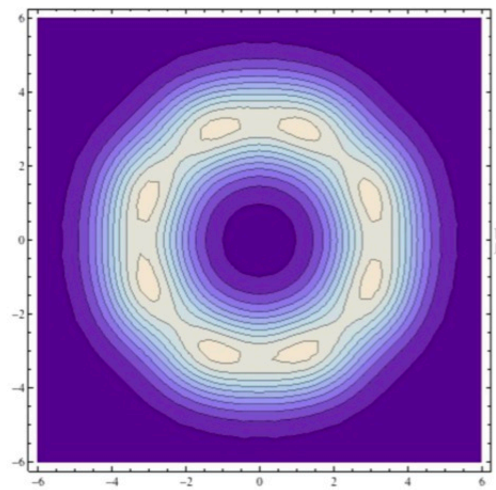




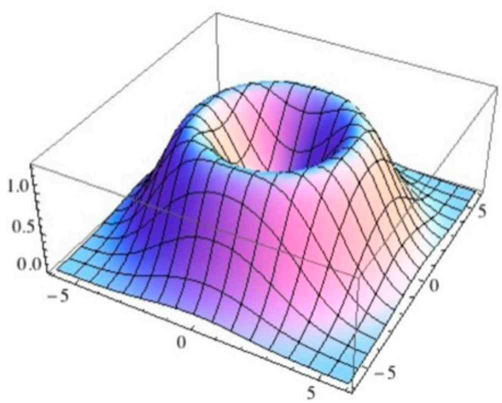
- 16 elliptical beams,
  a = 4.15 mm, b = 1.8 mm
  C_{16} = 0.00027
  PTV_{rim} = 0.00027
  $PTV_{integrated}$ = 0.0011

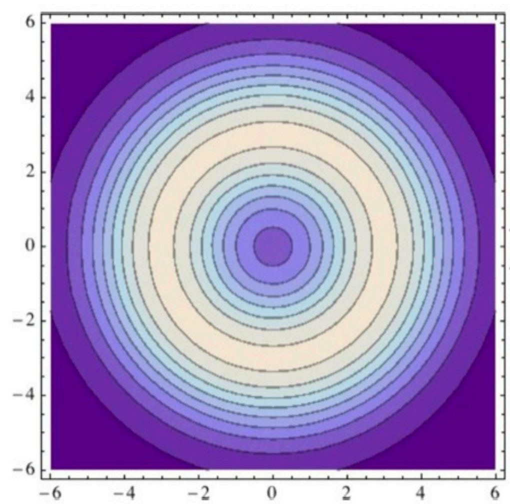
Arc-wobbled beam examples





- 4 arc-wobbled beams
  C_4 = 0.0051
  C_8 = -0.0297
  PTV_{rim} = 0.117
  $PTV_{integrated}$ = 0.16

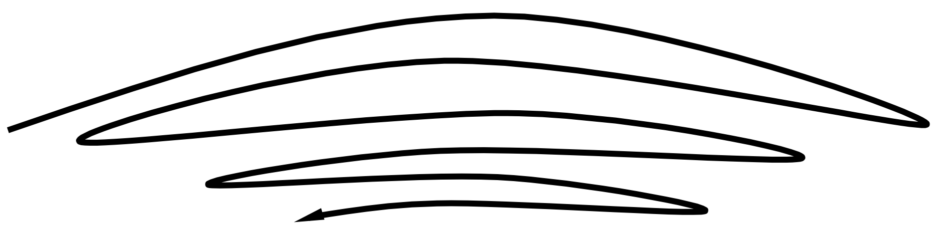




- 8 arc-wobbled beams
  C_8 = -0.00006
  PTV_{rim} = 0.00015
  $PTV_{integrated}$ = 0.00024
  These values are smaller than those obtained using 16 elliptical beams.

Some targets benefit by beam “zooming”

- For direct drive:
  - For a conventional scenario, deflectors could shift the beams as the implosion proceeds.
  - For a full-circle wobbler scenario, the amplitude of the wobbler-driven deflections could be reduced, thereby shrinking the circle on the target.
  - For a local-wobbler scenario, a steady inward motion could be imparted in a “switchback” geometry.
- For the X-target:
  - It is important to distribute the beam energy uniformly in the absorber, to avoid local depletion of absorbing material and enlarged ion range.
  - A local wobbler in a switchback geometry may be attractive.



switchback geometry

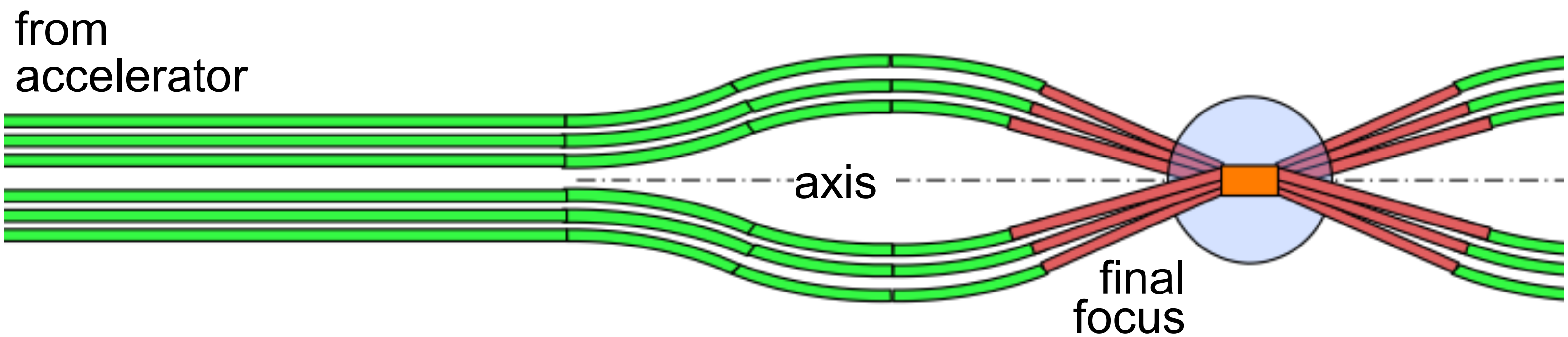
“Differential acceleration” in the final beam lines

By accelerating some beams “sooner” and others “later,” it is possible to simplify the beam line in some cases:

- Create the time delay between the “foot” and “main” pulses without resorting to large arcs in the main-pulse beam lines.
  - This may minimize beam bending, known to be a source of emittance growth in space-charge-dominated beams
- Arrange for the simultaneous arrival on target of a set of beams (*e.g.*, for the foot-pulse) without requiring that their path lengths be equal.
  - This may ease a long-standing challenge in designing a power plant.
  - The tens or hundreds of beams entering the chamber all need to be routed from one or two multi-beam accelerators or transport lines.
  - The resulting “railroad yard” is easier to design if path lengths need not be equal.

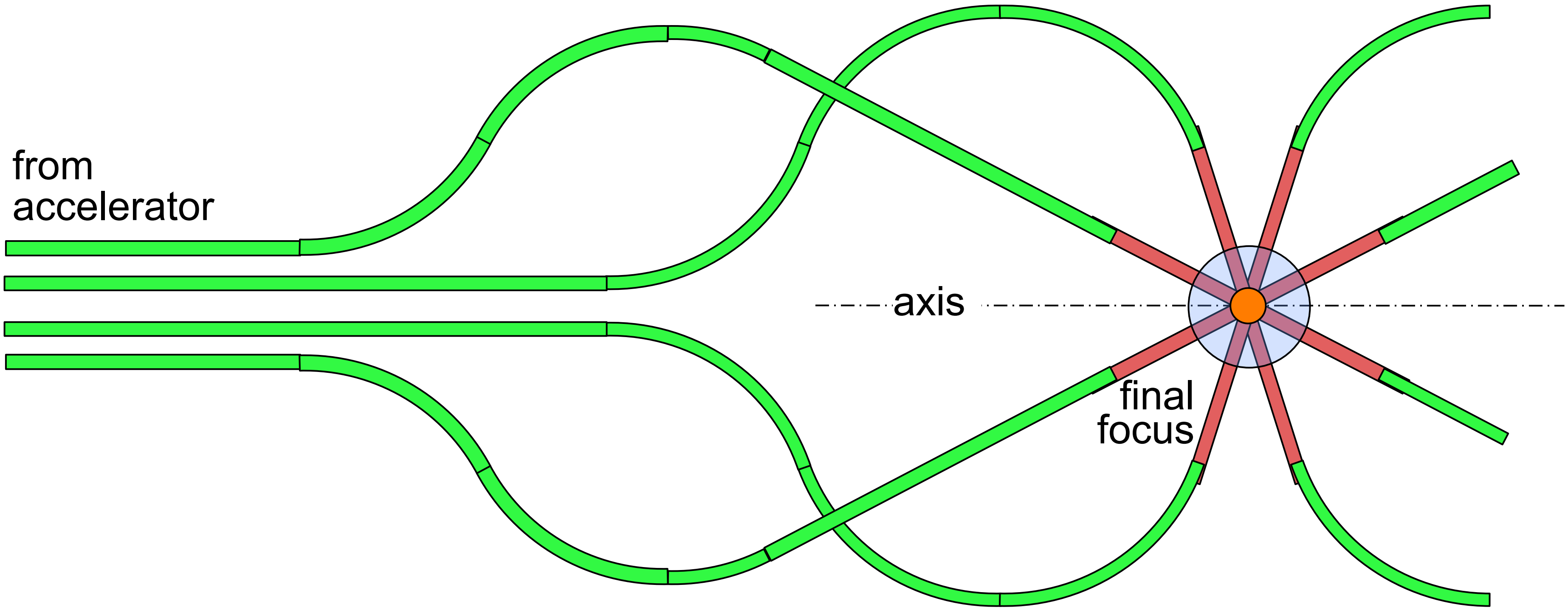
Schematic of final beamlines for ion indirect drive

(only representative beamlines are shown)



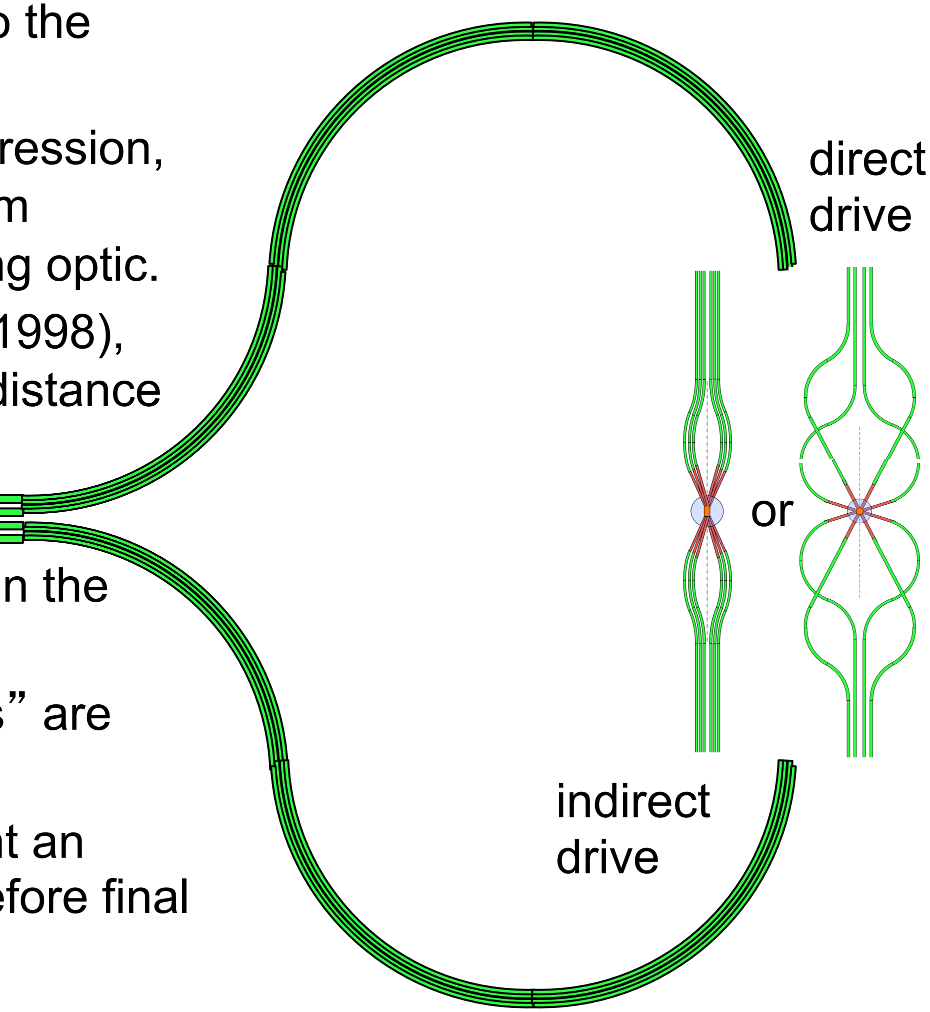
Schematic of final beamlines for ion direct drive

(only representative beamlines are shown)



With a single linac, arcs transport the beams to the two sides of the target (for most target concepts)

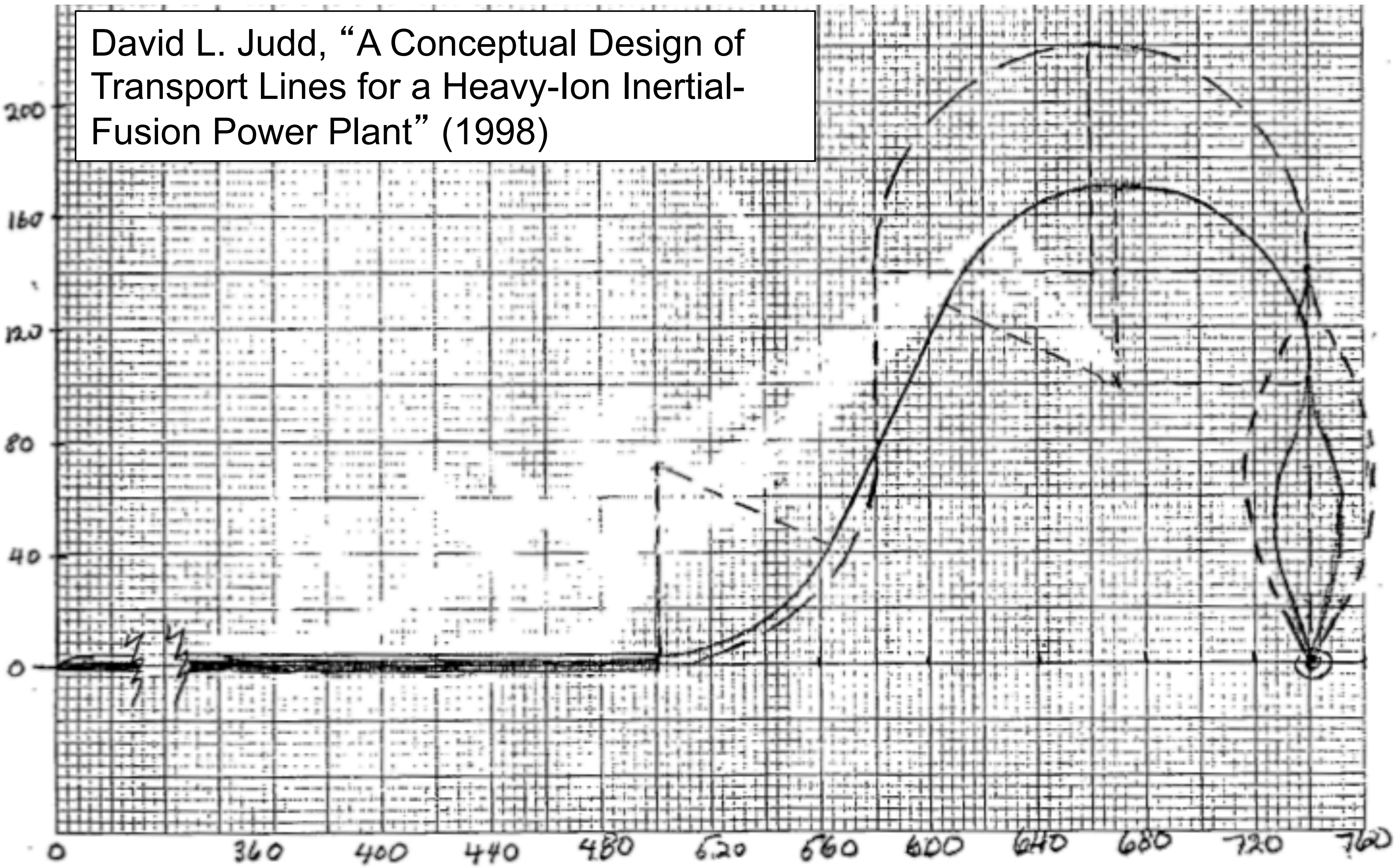
- In the final section of the driver, the beams are separated so that they may converge onto the target in an appropriate pattern.
- They also undergo non-neutral drift-compression, and ultimately “stagnate” to nearly-uniform energy, and pass through the final focusing optic.
- In the scenario examined by Dave Judd (1998), the arcs are ~ 600 m long, while the drift distance should be < 240 m.



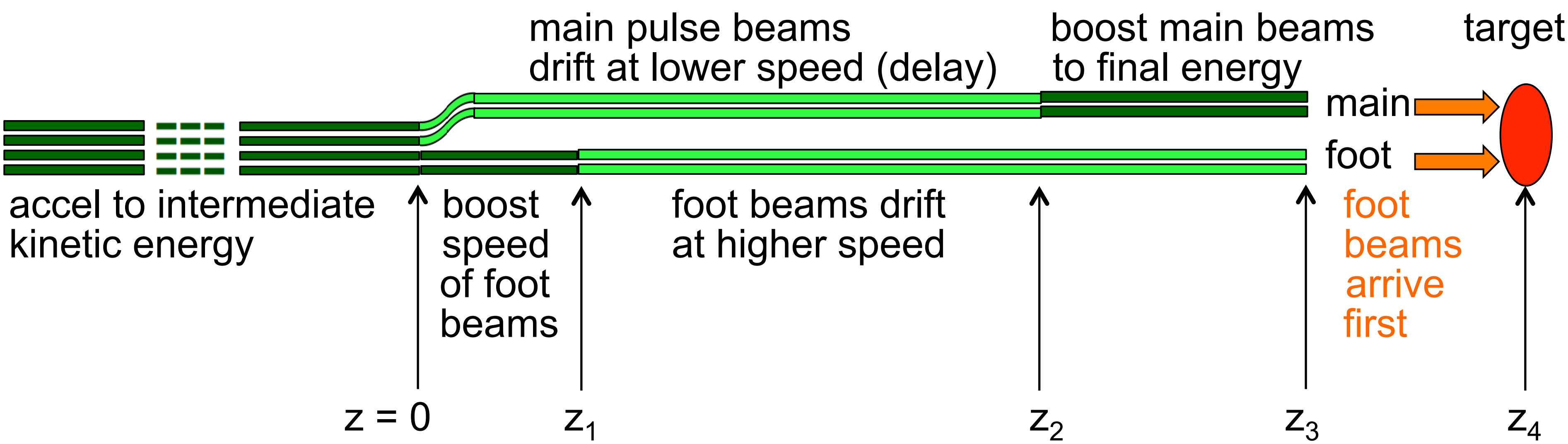
- Thus, the velocity “tilt” must be imposed in the arcs, or upon exit from the arcs.
- To maintain a quiescent beam, “ear fields” are needed in the arcs.
- For pulse-shaping, the arcs may represent an opportunity to pre-configure the beams before final compression.

If a foot pulse of lower K.E. is needed, those beams are "traditionally" extracted from the linac early and routed via shorter arcs

David L. Judd, "A Conceptual Design of Transport Lines for a Heavy-Ion Inertial-Fusion Power Plant" (1998)



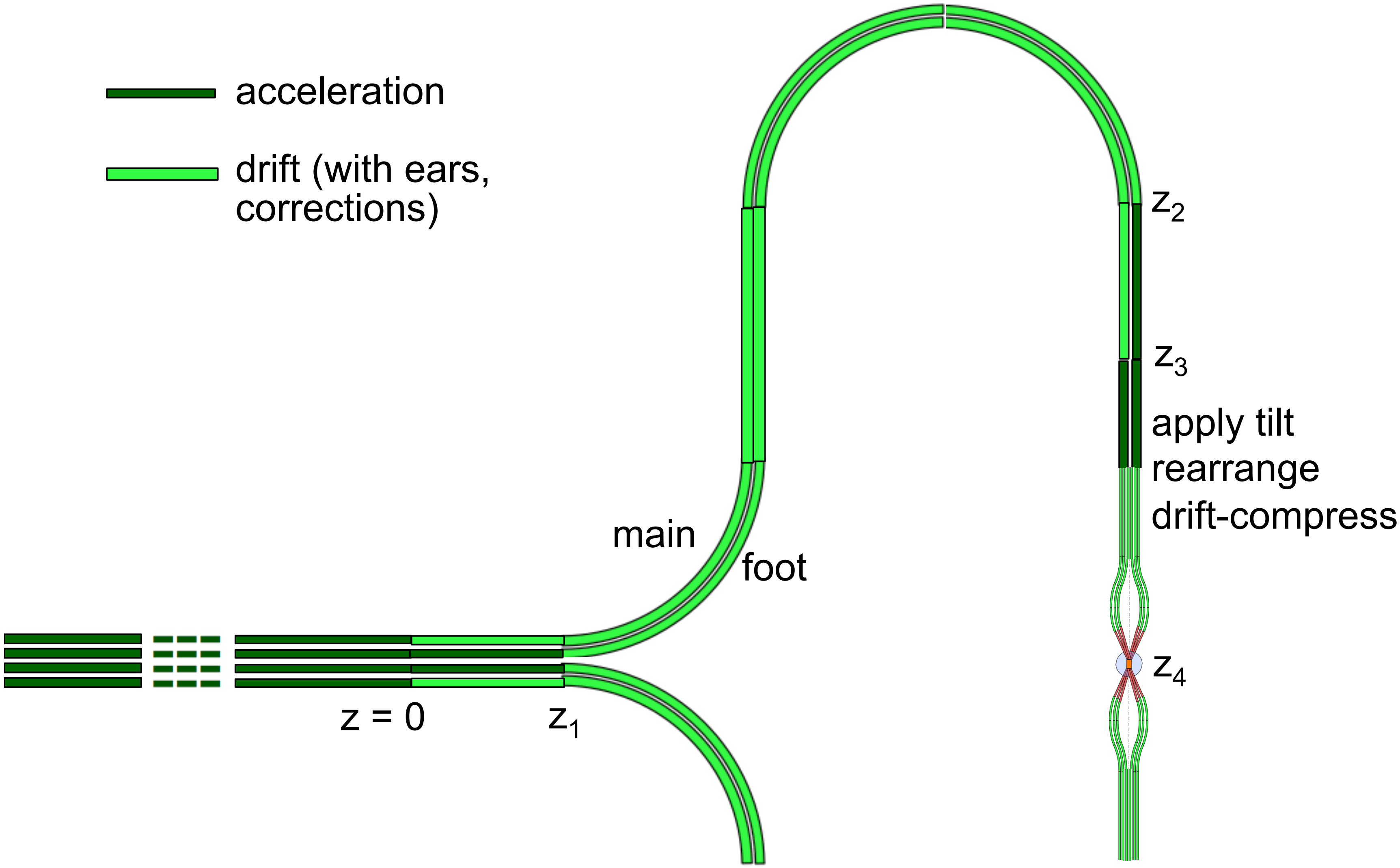
Delay between foot and main pulses can be inserted in a nearly linear system



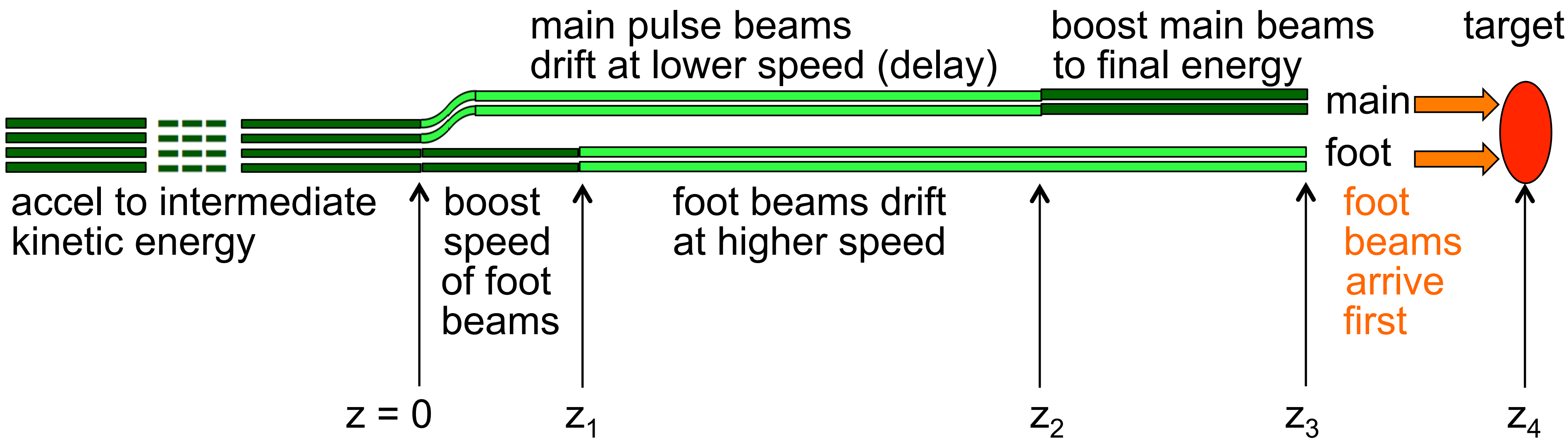
This concept may be useful …

- if two linacs are used, one from each side
- with a single linac, for a single-sided target
- with a single linac, for a two-sided target (see next slide)

A single linac with common arcs could drive a 2-sided target



Example: for an indirect-drive target requiring two beam energies



Aion = 208.980 amu

Accelgradient = 3.0 MV/m

Int. Vz = 48.046 m/us, beta = 0.1603

Foot Vz = 52.632 m/us, beta = 0.1756

Main Vz = 60.774 m/us, beta = 0.2027

Int. Ek = 2.5 GeV

Foot Ek = 3.0 GeV

Main Ek = 4.0 GeV

z1 = 0.167 km

z2 = 0.542 km

z3 = 1.042 km

z4 = 1.242 km

t1foot = 3310.884 ns

t1main = 3468.888 ns

t2foot = 10435.840 ns

t2main = 11273.886 ns

t3foot = 19935.780 ns

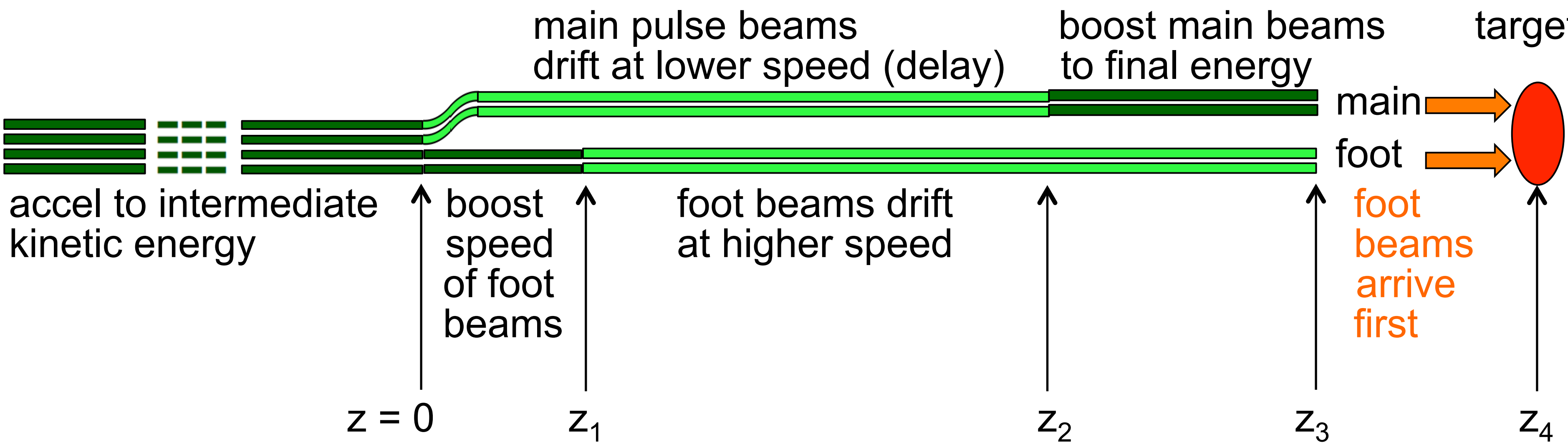
t3main = 20463.353 ns

t4foot = 23735.757 ns

t4main = 23754.229 ns

delay = 18.473 ns

Example: for an X-target requiring a single beam energy



Aion = 84.910 amu	z1 = 0.333 km	t1foot = 1978.104 ns
Accelgradient = 3.0 MV/m	z2 = 0.433 km	t1main = 2018.490 ns
Int. Vz = 165.140 m/us, beta = 0.5509	z3 = 0.767 km	t2foot = 2559.895 ns
Foot Vz = 171.883 m/us, beta = 0.5733	z4 = 1.067 km	t2main = 2624.038 ns
Main Vz = 171.883 m/us, beta = 0.5733		t3foot = 4499.198 ns
Int. Ek = 12.0 GeV		t3main = 4602.142 ns
Foot Ek = 13.0 GeV		t4foot = 6244.571 ns
Main Ek = 13.0 GeV		t4main = 6347.515 ns
		delay = 102.944 ns